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Meyer et al.

(10) **Patent No.: US 6,769,312 B2**
(45) **Date of Patent: Aug. 3, 2004**

(54) **MULTI-AXIS LOAD CELL BODY**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

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(22) Filed: **Jul. 17, 2001**

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Related U.S. Application Data

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(51) **Int. Cl.**^{7} **G01D 7/00**

(52) **U.S. Cl.** **73/862.042**

(58) **Field of Search** 73/862.041, 862.042, 73/862.043, 862.044, 862.045, 146

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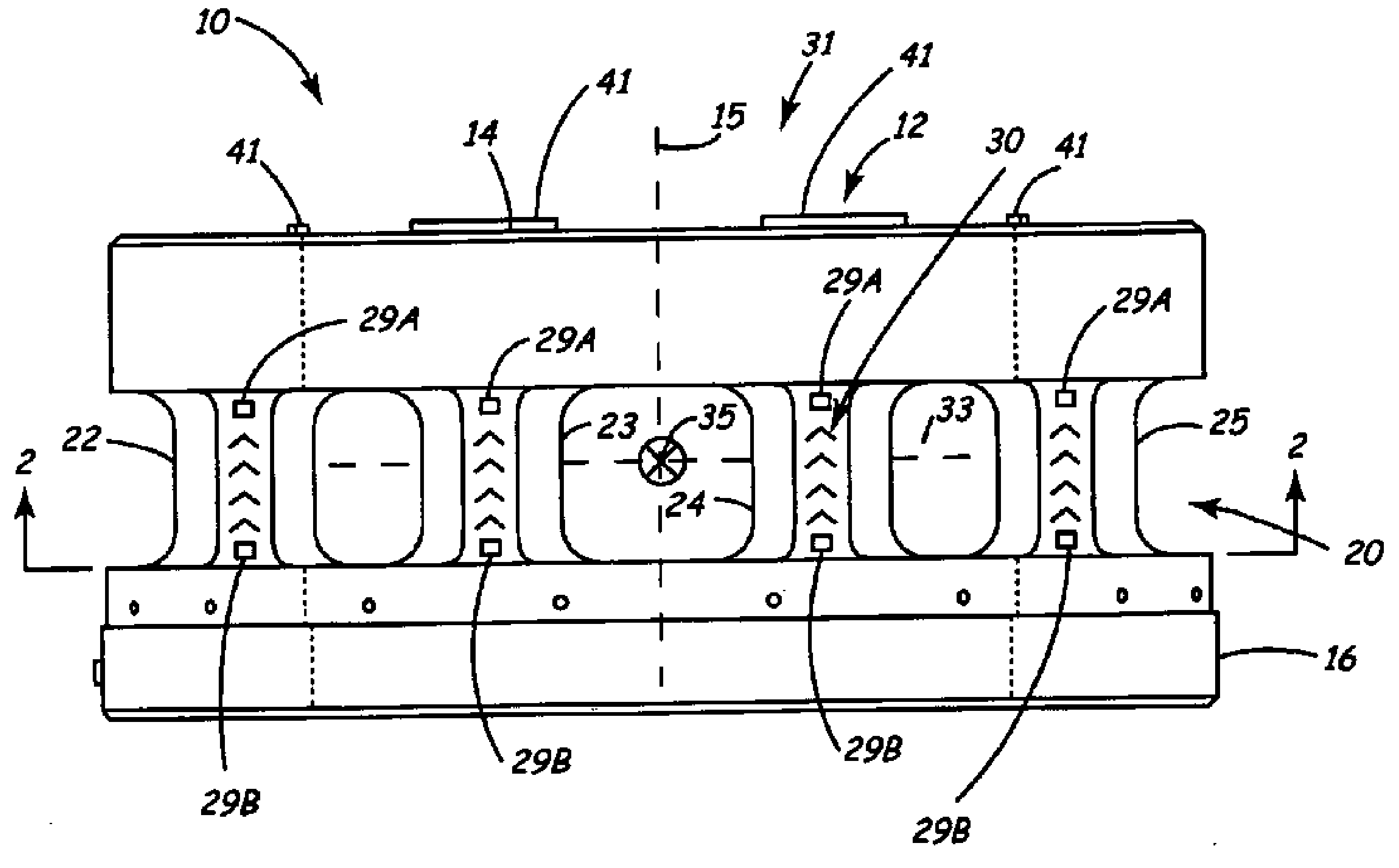
(57) **ABSTRACT**

A load cell comprises two rings having at least three tubes extending from the first ring to the second ring. Sensors are mounted on the tubes to measure strain of the load cell body in a plurality of directions. The load cell can further be mounted on a vehicle spindle to measure forces and moments of a wheel assembly at the spindle as a vehicle is operated.

27 Claims, 15 Drawing Sheets-



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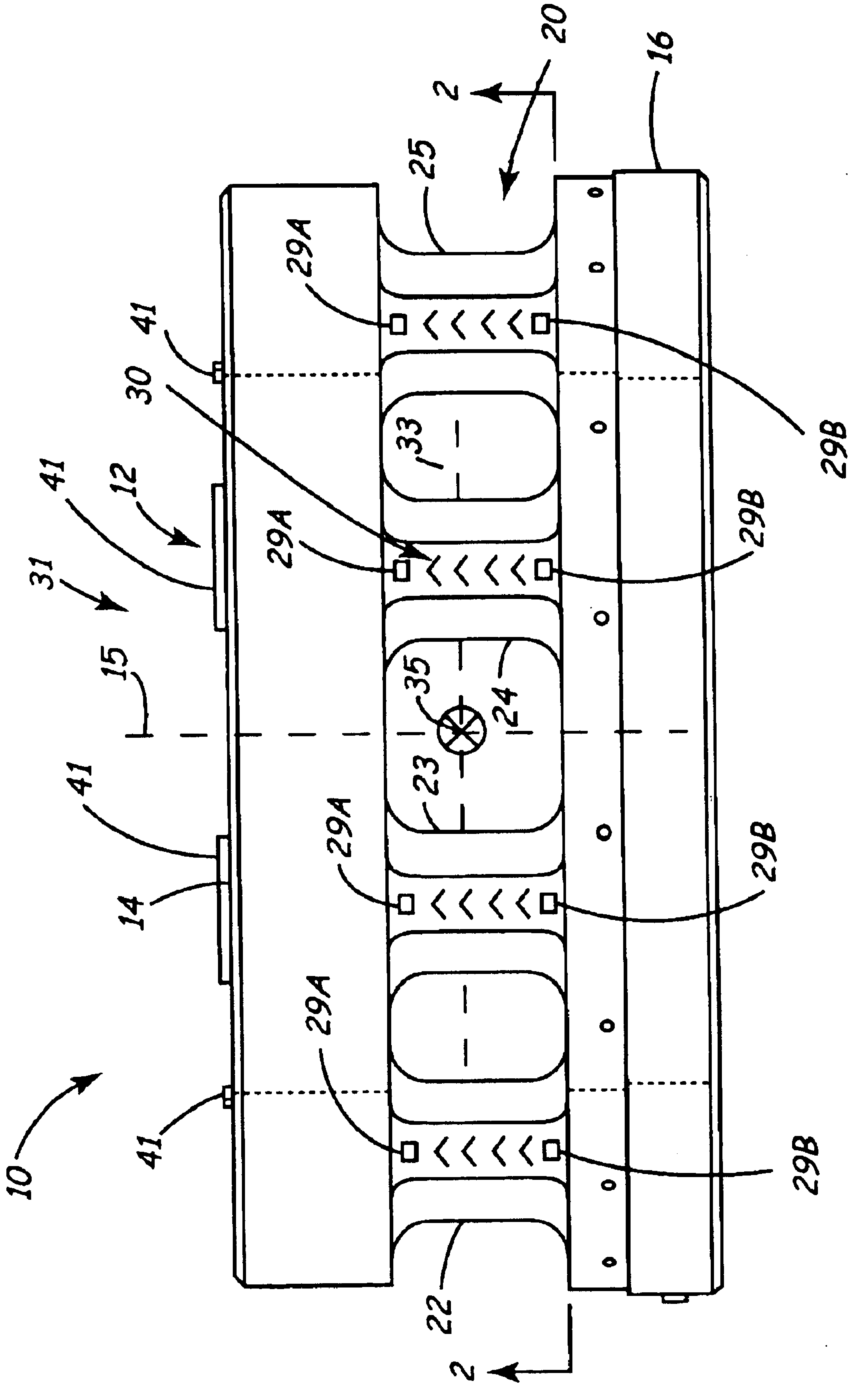
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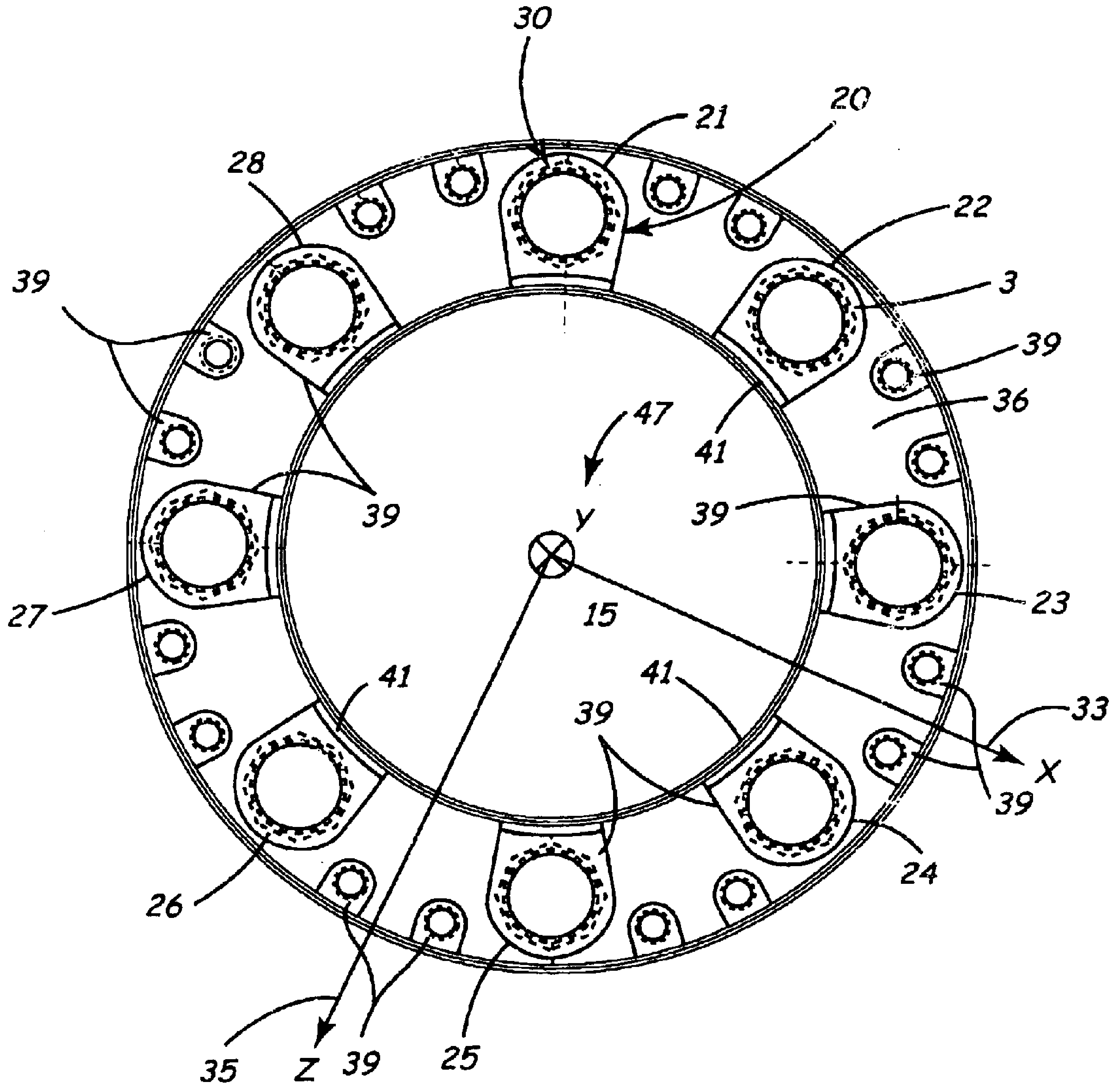
41
29A
29B
22
2
14
41
29A
29B
15
31
41
12
29A
29B
30
41
33
35
23
24
29A
29B
25
20
2
16

FIG. 1A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21
20
28
22
39
3
39
36
47
41
39
y
39
27
15
23
41
41
33
39
x
39
39
26
24
35
z
39
25

FIG. 1B

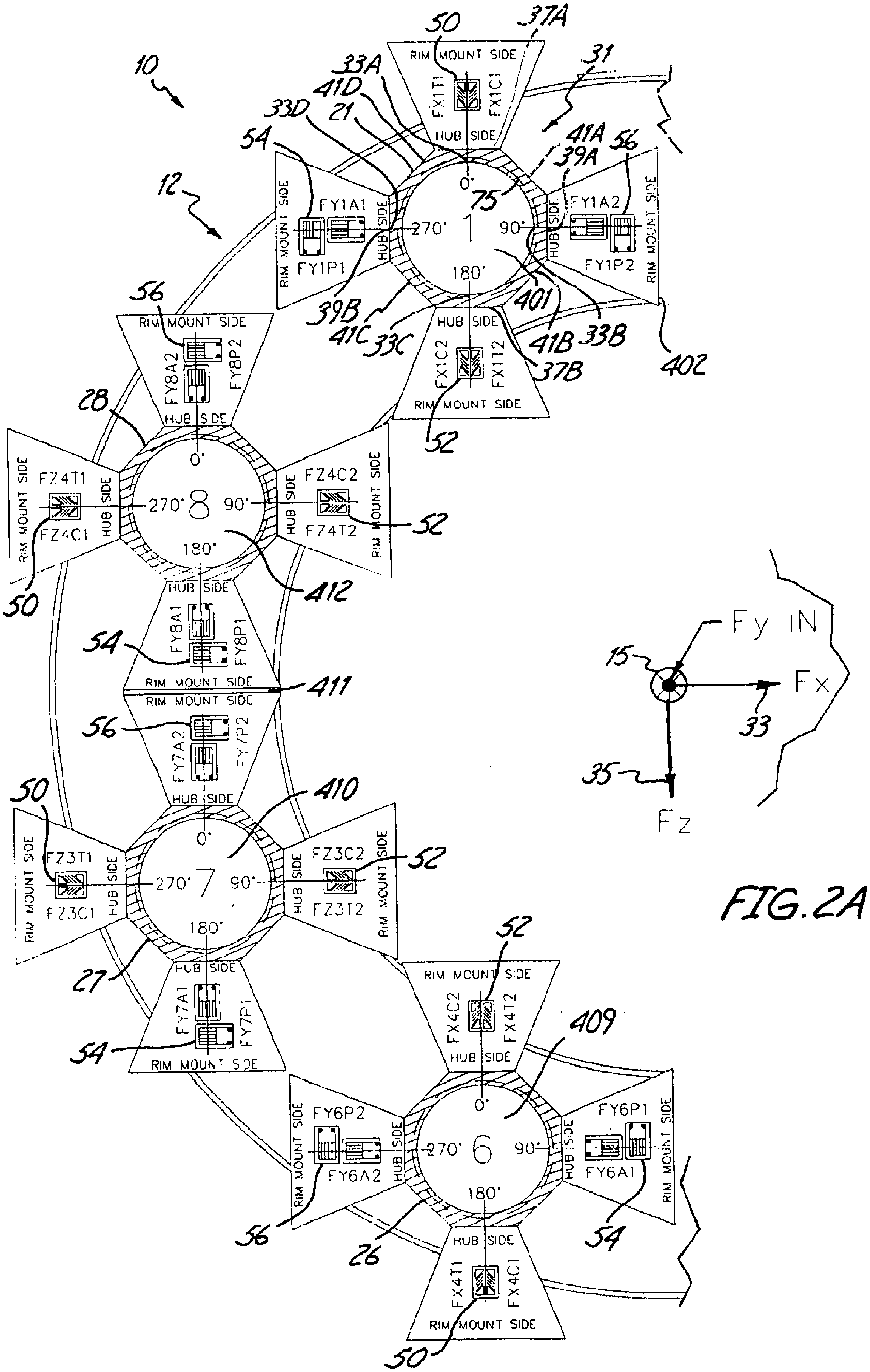
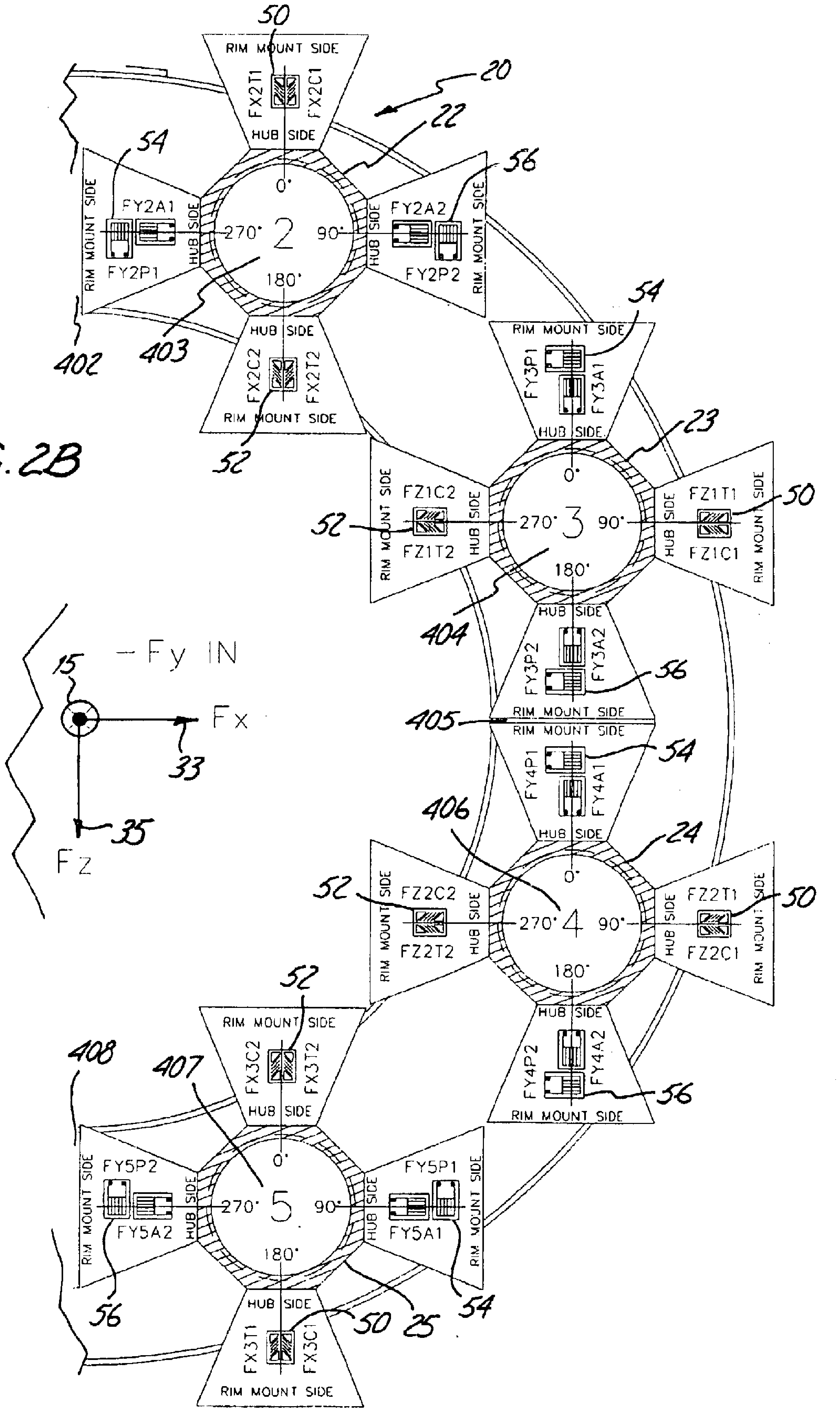

10
12
50
37A
31
33A
41D
21
33D
54
41A
39A
56
RIM MOUNT SIDE
FX1T1
FX1C1
HUB SIDE
0°
75
270°
1
90°
180°
FY1A1
FY1P1
FY1A2
FY1P2
39B
41C
33C
401
41B
33B
37B
402
FX1C2
FX1T2
52
FY8A2
FY8P2
28
FZ4T1
FZ4C1
8
FZ4C2
FZ4T2
412
FY8A1
FY8P1
411
FY7A2
FY7P2
410
FZ3T1
FZ3C1
7
FZ3C2
FZ3T2
27
FY7A1
FY7P1
FX4C2
FX4T2
409
FY6P2
FY6A2
6
FY6P1
FY6A1
26
FX4T1
FX4C1
Fy IN
15
Fx
33
35
Fz

FIG.2A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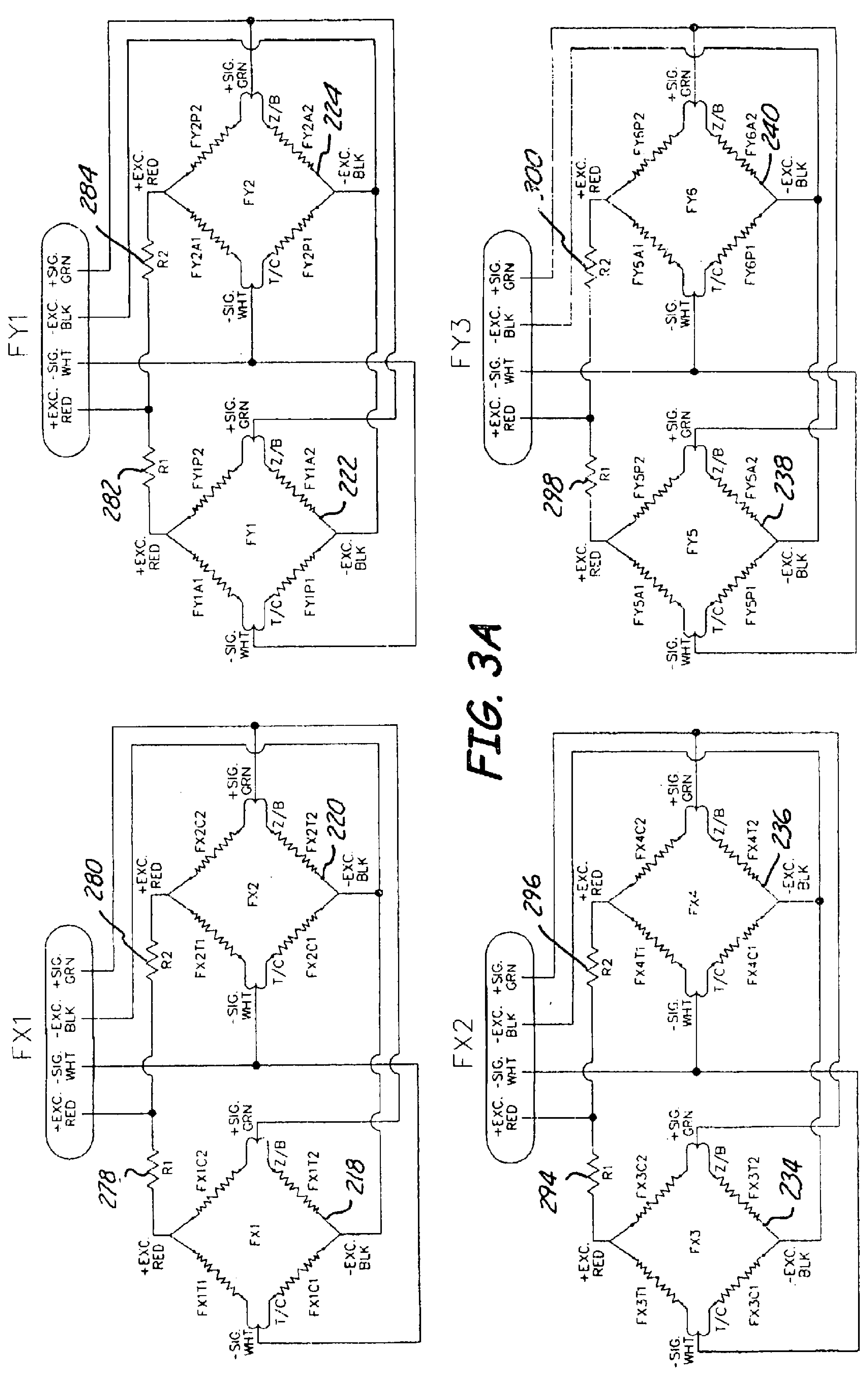
RIM MOUNT SIDE
FX2T1
FX2C1
HUB SIDE
20
22
54
56
FY2A1
FY2P1
FY2A2
FY2P2
0°
270°
2
90°
180°
RIM MOUNT SIDE
HUB SIDE
402
403
FX2C2
FX2T2
52
FY3P1
FY3A1
23
FZ1C2
FZ1T2
FZ1T1
FZ1C1
3
404
FY3P2
FY3A2
405
FY4P1
FY4A1
406
24
FZ2C2
FZ2T2
FZ2T1
FZ2C1
4
FY4P2
FY4A2
408
407
FX3C2
FX3T2
FY5P2
FY5A2
FY5P1
FY5A1
5
FX3T1
FX3C1
25
15
−Fy IN
Fx
33
35
Fz

FIG. 2B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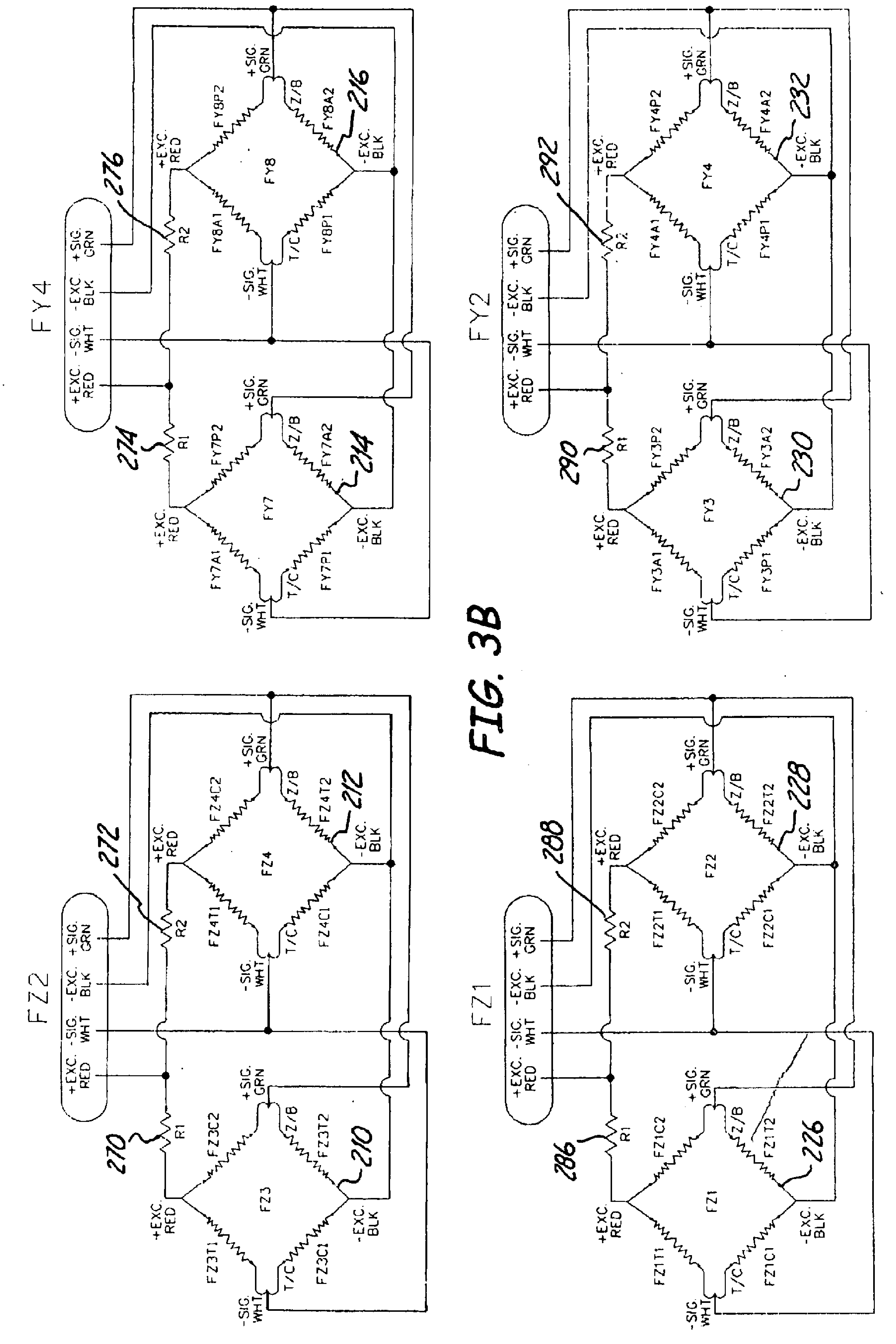
-SIG. WHT
-EXC. BLK
+SIG. GRN
R1
R2
282
284
FY1
FY1P2
FY1A2
FY1A1
FY1P1
Z/B
T/C
222
FY2
FY2P2
FY2A2
FY2A1
FY2P1
224
FY3
FY5
FY5P2
FY5A2
FY5A1
FY5P1
238
298
FY6
FY6P2
FY6A2
FY5A1
FY6P1
240
300
FX1
FX1
FX1C2
FX1T2
FX1T1
FX1C1
218
278
FX2
FX2C2
FX2T2
FX2T1
FX2C1
220
280
FX2
FX3
FX3C2
FX3T2
FX3T1
FX3C1
234
294
FX4
FX4C2
FX4T2
FX4T1
FX4C1
236
296

FIG. 3A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-EXC. BLK
+SIG. GRN
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R2
R1
274
FY8
FY8P2
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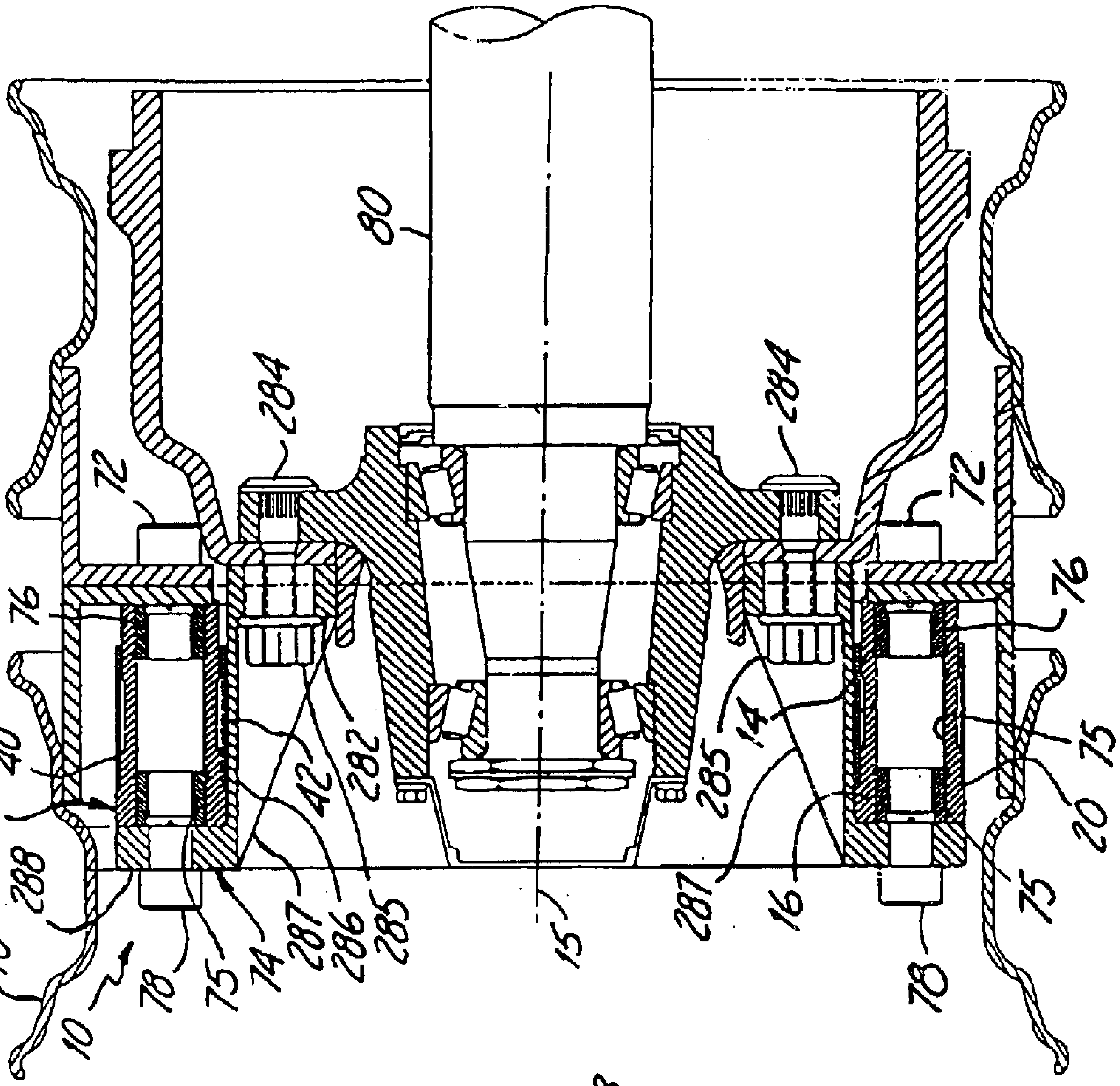
FY8A1
FY8P1
216
Z/B
T/C
FY7
FY7P2
FY7A2
FY7A1
FY7P1
214
FY2
292
290
FY4P2
FY4A2
FY4A1
FY4P1
232
FY3
FY3P2
FY3A2
FY3A1
FY3P1
230
FZ2
272
270
FZ4
FZ4C2
FZ4T2
FZ4T1
FZ4C1
212
FZ3
FZ3C2
FZ3T2
FZ3T1
FZ3C1
210
FZ1
288
286
FZ2C2
FZ2T2
FZ2T1
FZ2C1
228
FZ1C2
FZ1T2
FZ1T1
FZ1C1
226

FIG. 3B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284
284
72
72
76
76
40
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288
70
10
78
75
74
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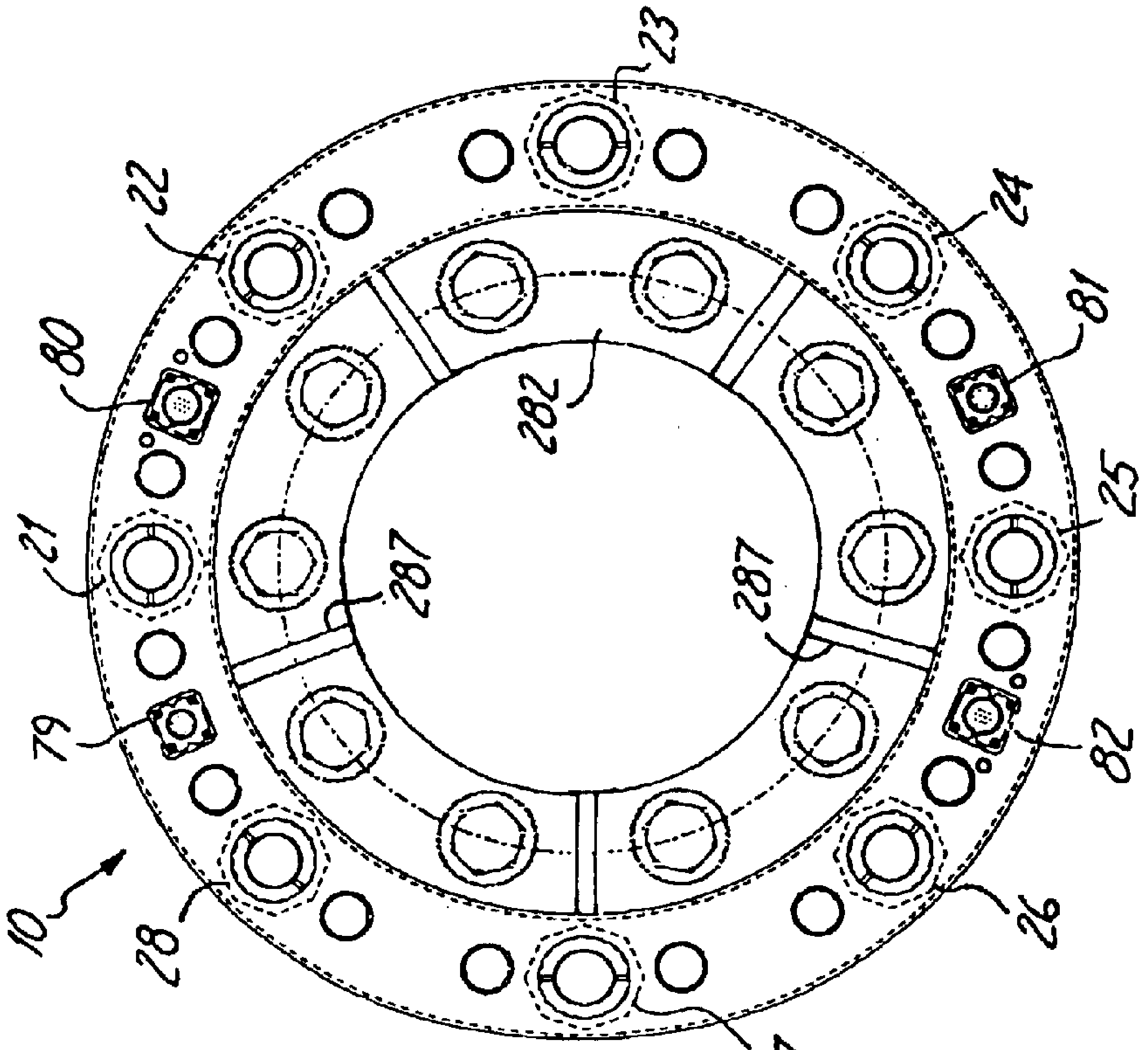
42
282
285
15
14
285
287
16
75
20
75
78

FIG.4A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81
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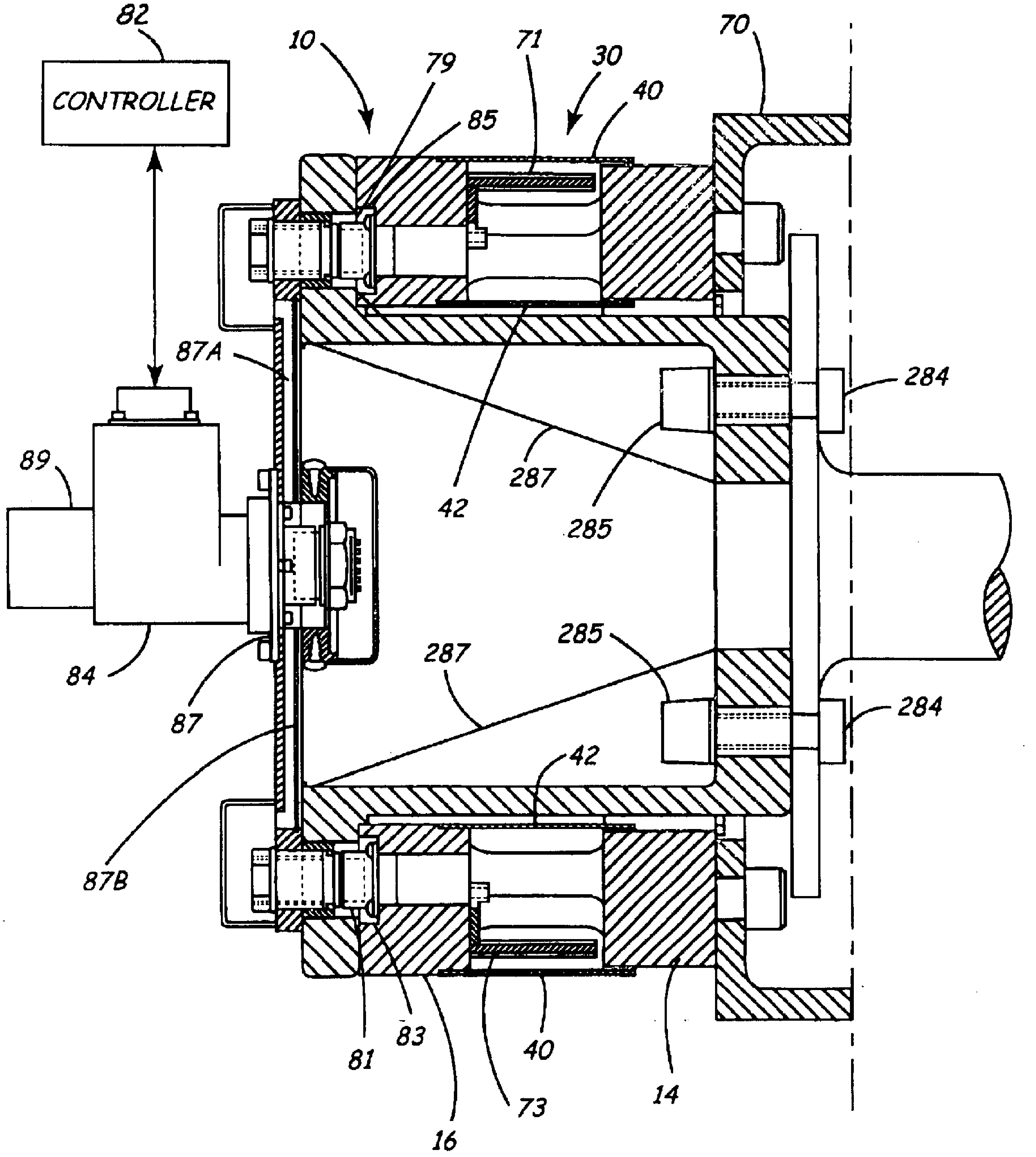
287
79
82
10
28
26
27

FIG.4B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CONTROLLER
10
79
71
30
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70
85
87A
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89
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84
87
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287
284
42
87B
81
83
40
14
73
16

FIG. 5

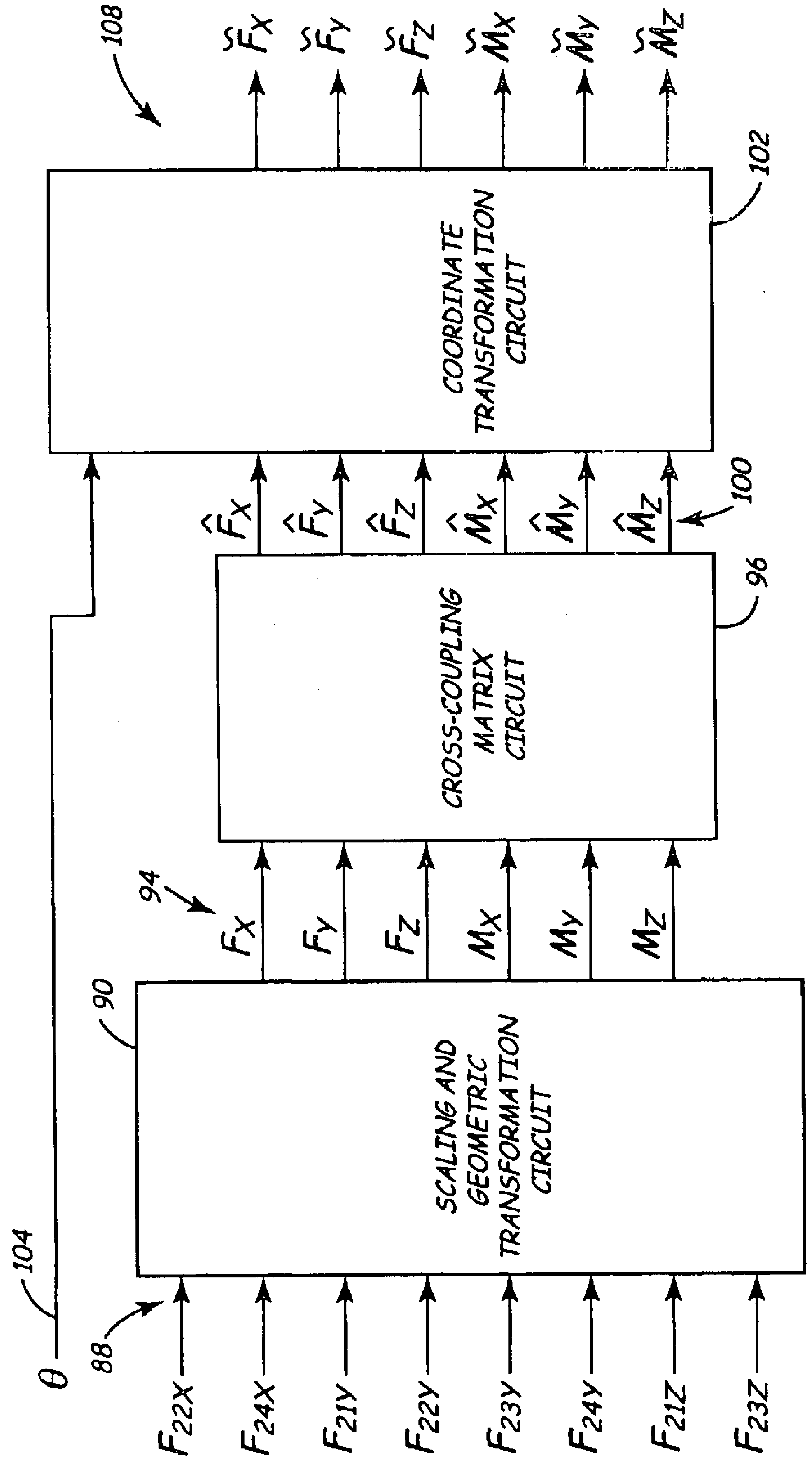
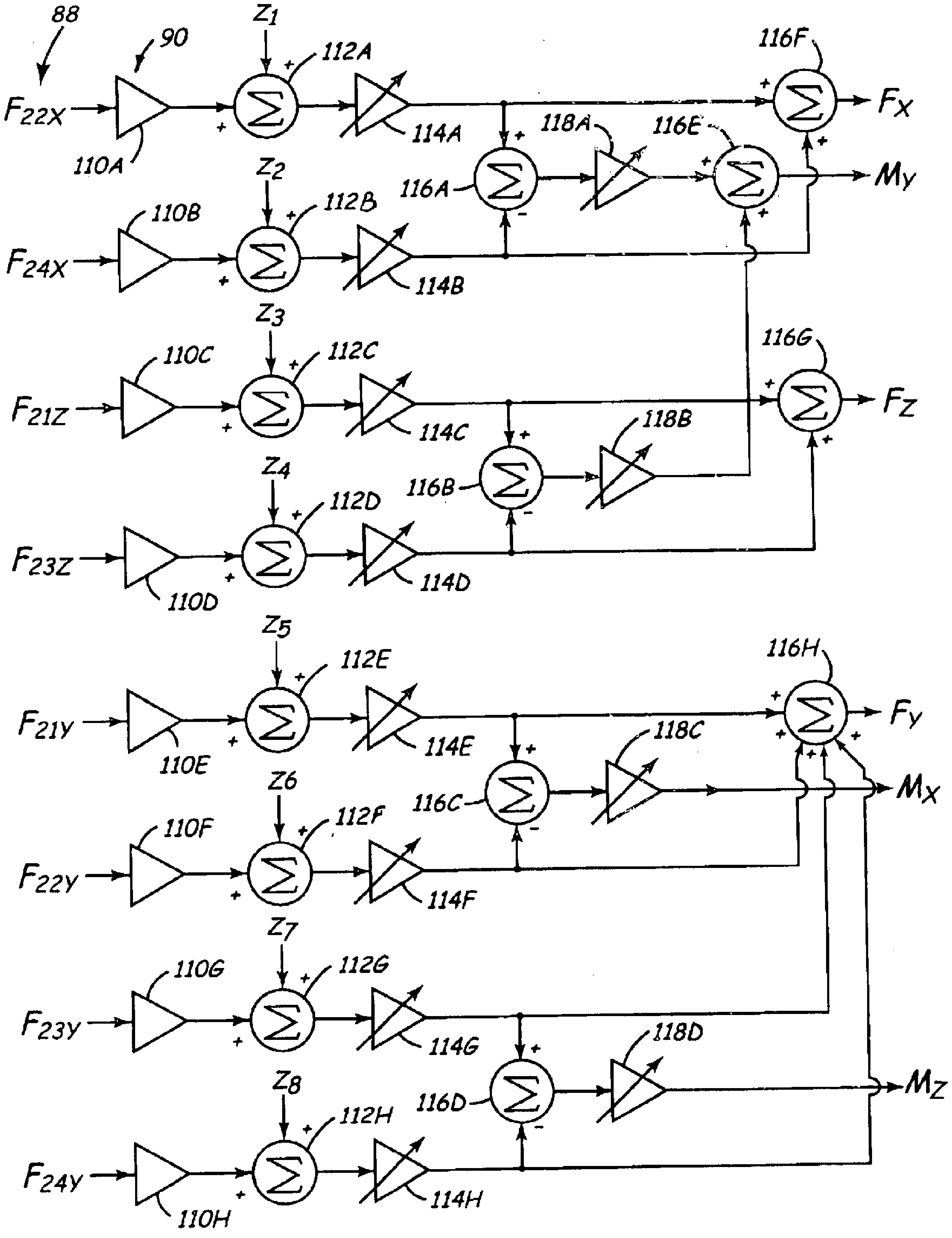

θ
104
88
F_{22X}
F_{24X}
F_{21Y}
F_{22Y}
F_{23Y}
F_{24Y}
F_{21Z}
F_{23Z}
90
SCALING AND GEOMETRIC TRANSFORMATION CIRCUIT
94
F_X
F_Y
F_Z
M_X
M_Y
M_Z
96
CROSS-COUPLING MATRIX CIRCUIT
100
$\hat{F}_X$
$\hat{F}_Y$
$\hat{F}_Z$
$\hat{M}_X$
$\hat{M}_Y$
$\hat{M}_Z$
102
COORDINATE TRANSFORMATION CIRCUIT
108
$\tilde{F}_X$
$\tilde{F}_Y$
$\tilde{F}_Z$
$\tilde{M}_X$
$\tilde{M}_Y$
$\tilde{M}_Z$

FIG. 6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90
F_{22X}
110A
Z_1
112A
114A
116F
F_X
118A
116E
116A
M_Y
Z_2
110B
112B
F_{24X}
114B
Z_3
110C
112C
116G
F_{21Z}
114C
F_Z
118B
Z_4
116B
112D
F_{23Z}
114D
110D
Z_5
112E
116H
F_{21Y}
114E
F_Y
110E
118C
Z_6
116C
M_X
110F
112F
F_{22Y}
114F
Z_7
110G
112G
F_{23Y}
114G
118D
Z_8
116D
M_Z
112H
F_{24Y}
114H
110H

FIG. 7

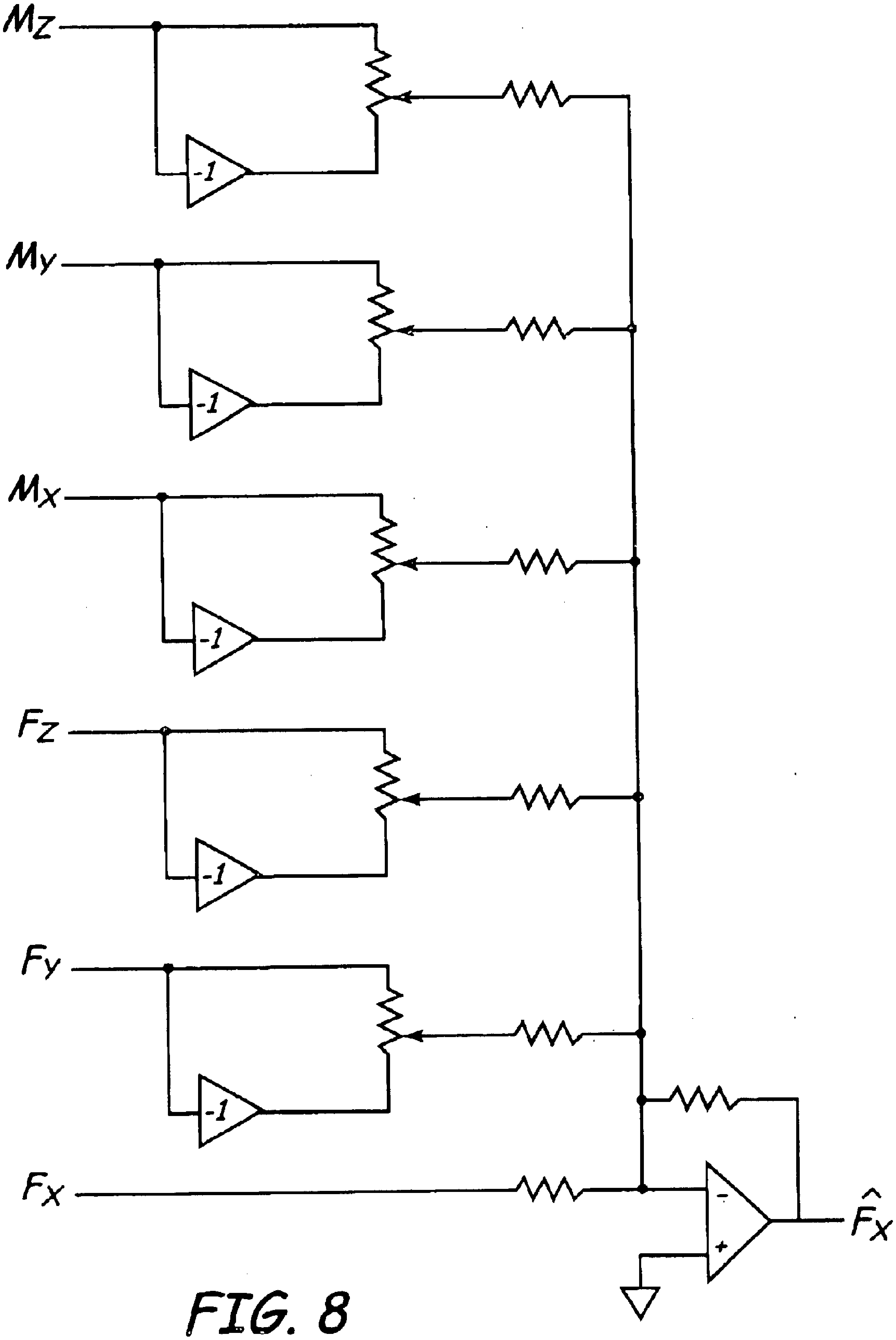
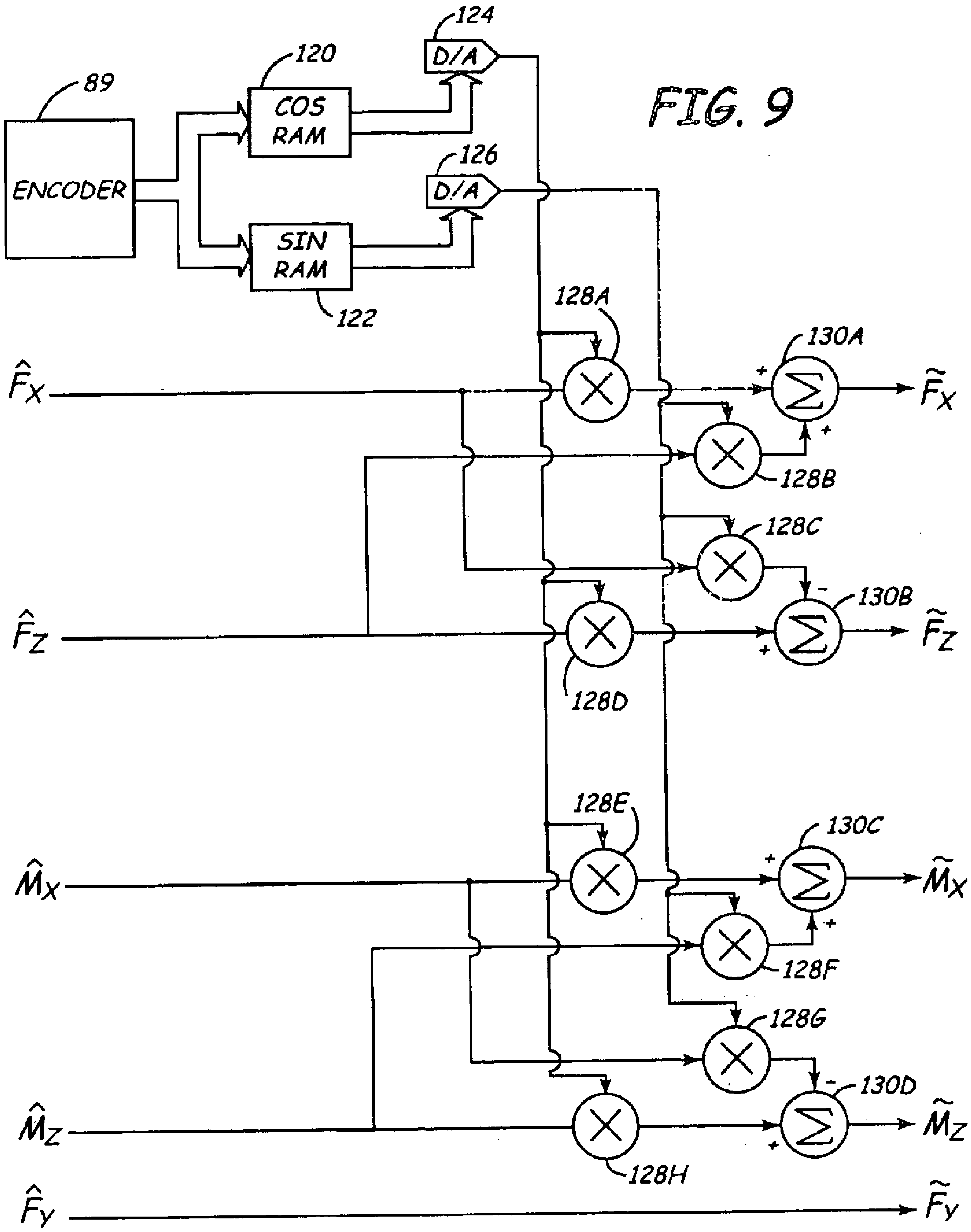


FIG. 8

FIG. 9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ENCODER
120
COS RAM
122
SIN RAM
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D/A
126
D/A
128A
128B
128C
128D
128E
128F
128G
128H
130A
130B
130C
130D
$\hat{F}_X$
$\hat{F}_Z$
$\hat{M}_X$
$\hat{M}_Z$
$\hat{F}_Y$
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$\tilde{M}_X$
$\tilde{M}_Z$
$\tilde{F}_Y$
+
-

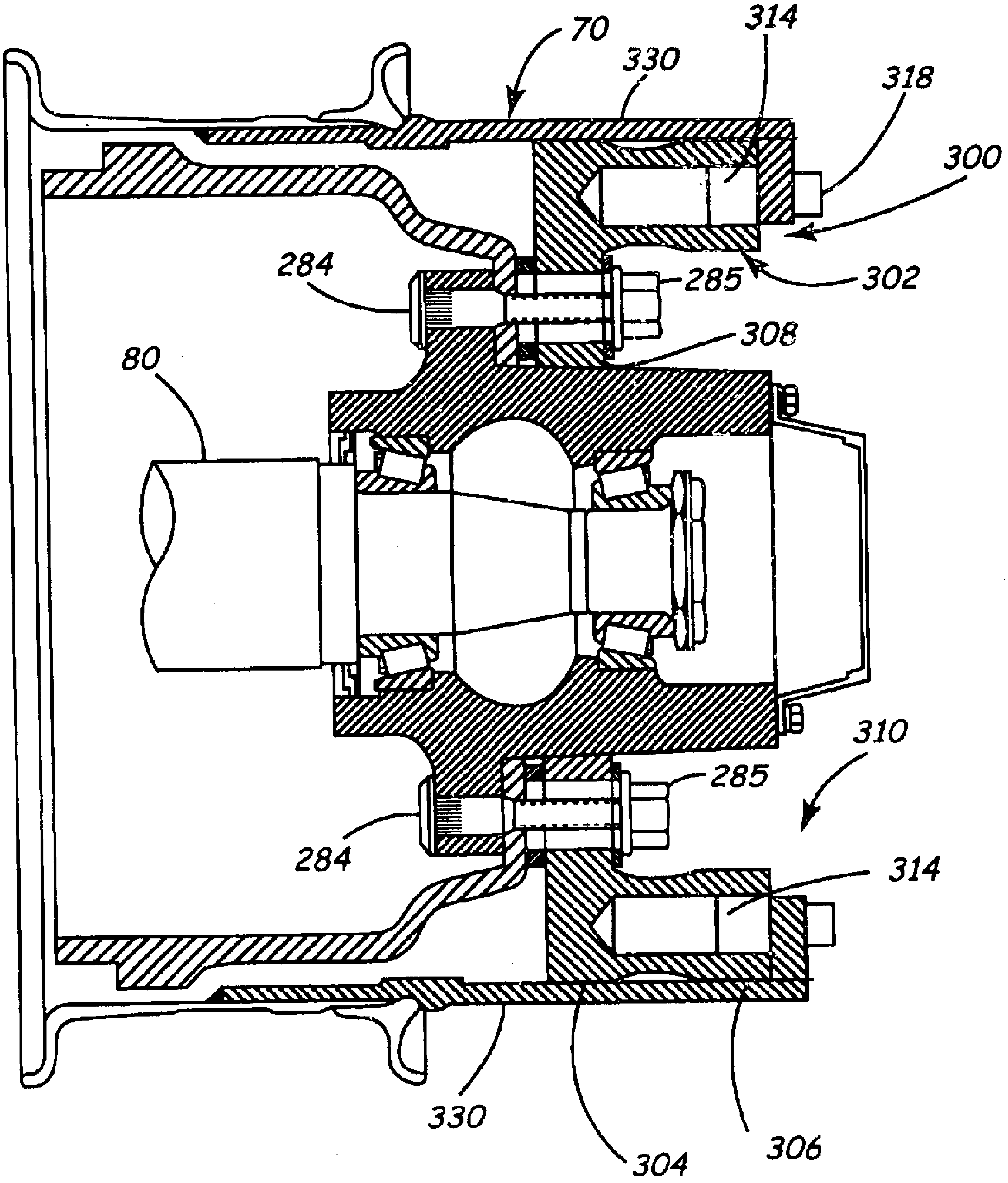


FIG. 10A

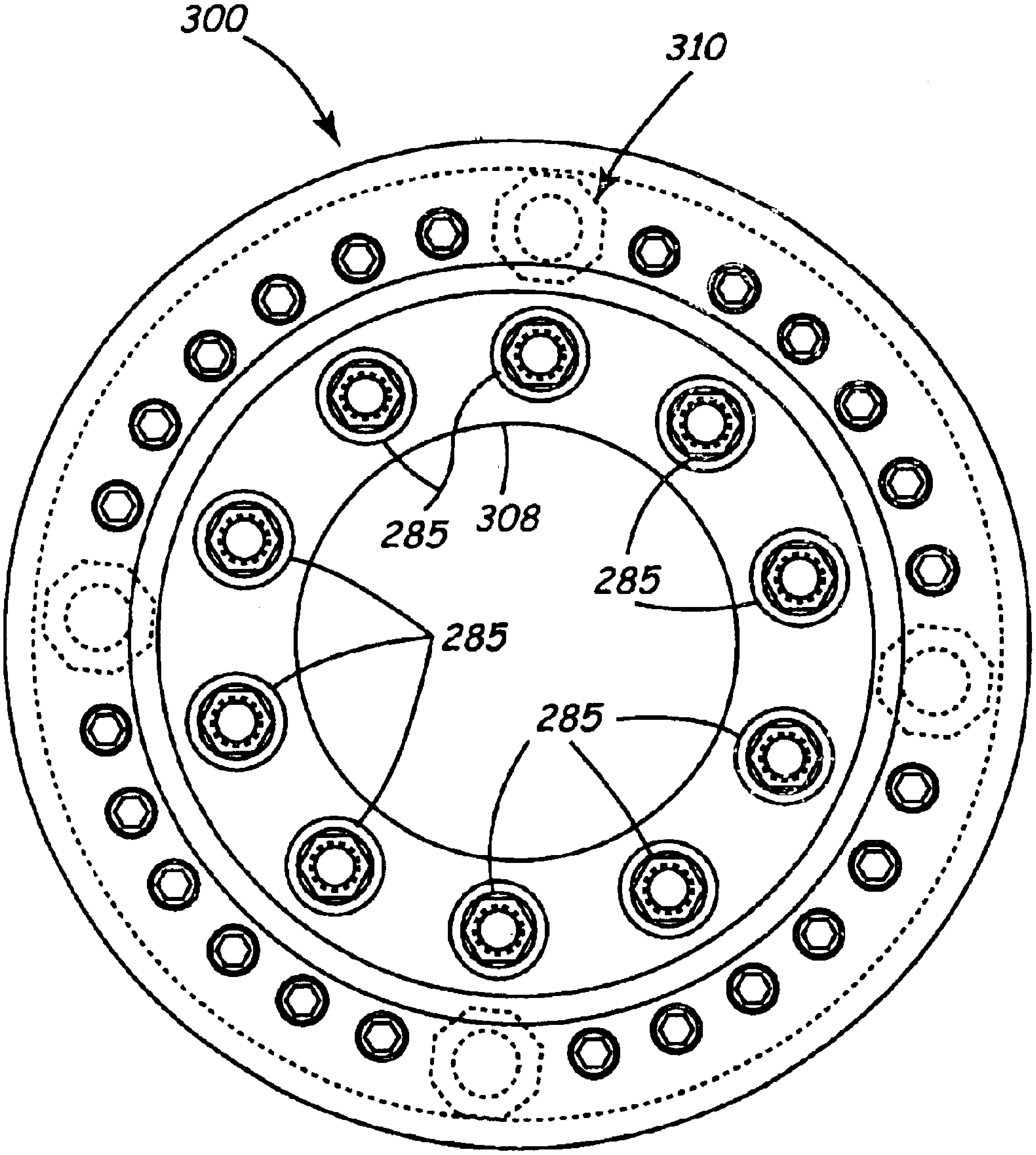
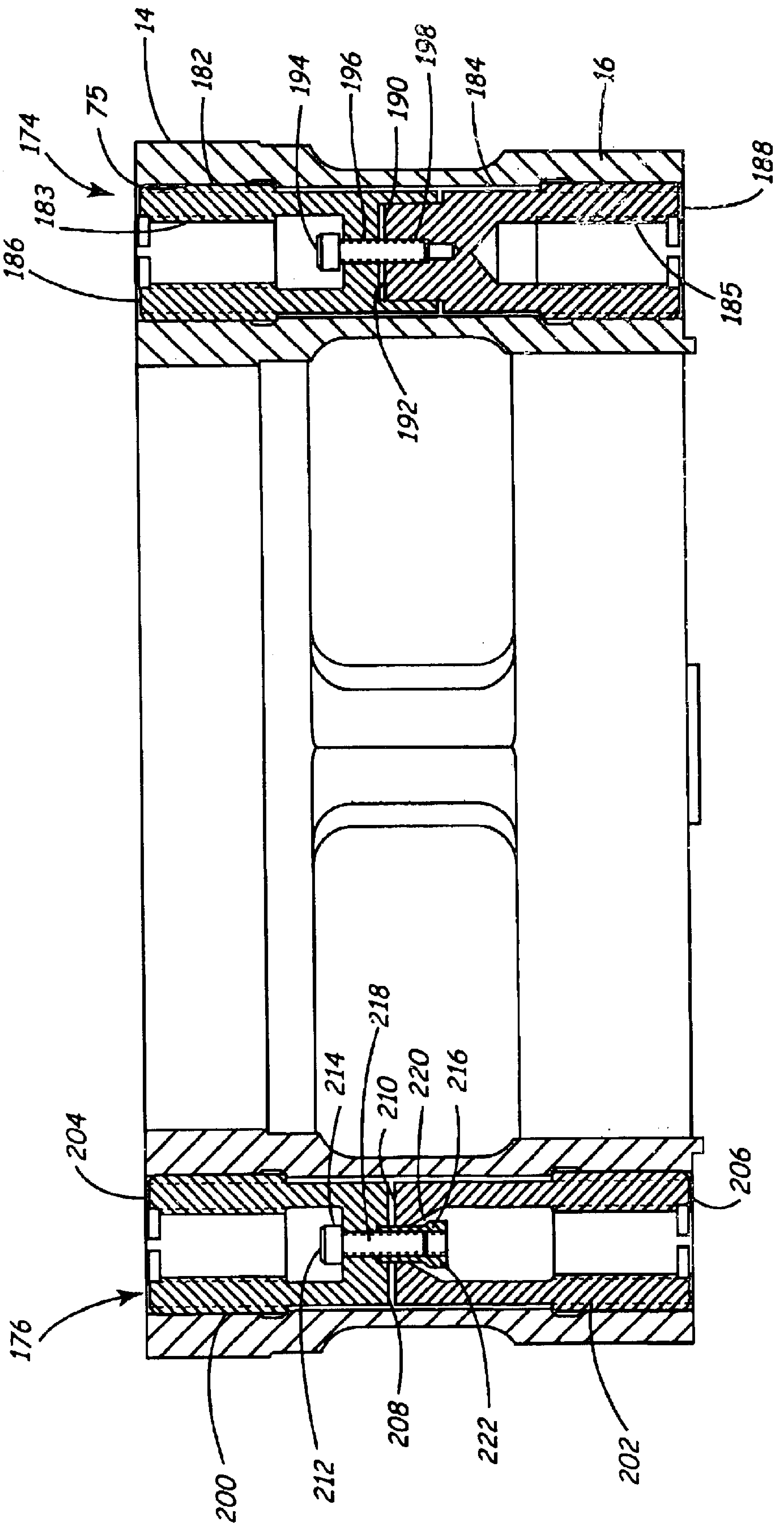


FIG. 10B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220
216
206
176
200
212
208
222
202

FIG. 11

MULTI-AXIS LOAD CELL BODY

CROSS-REFERENCE TO RELATED APPLICATION

The present application is based on and claims the benefit of U.S. provisional patent application Ser. No. 60/252,866, filed Nov. 22, 2000, the content of which is hereby incorporated by reference in its entirety.

BACKGROUND OF THE INVENTION

The present invention relates to a load cell that transmits and measures linear forces along and moments about three orthogonal axes. More particularly, a compact load cell body suitable for application as a wheel force transducer is disclosed.

Wheel force transducer or load cells for measuring forces along or moments about three orthogonal axes are known. The wheel force transducer typically is mounted between and to a vehicle spindle and a portion of a vehicle rim. The transducer measures forces and moments reacted through a wheel assembly at the spindle as the vehicle is operated.

One form of a wheel force transducer that has enjoyed substantial success and critical acclaim has been the Swift® transducer sold by MTS Systems Corporation of Eden Prairie, Minn. and is described in detail in U.S. Pat. Nos. 5,969,268 and 6,038,933. Generally, this transducer includes a load cell body having a rigid central member, a rigid annular ring and a plurality of tubular members extending radially and joining the central member to the annular ring. A plurality of sensing circuits are mounted to the plurality of tubular members. The rigid central member is mounted to the vehicle spindle, while the annular ring is attached to the vehicle rim. An encoder measures the angular position of the load cell body allowing the forces transmitted through the radial tubular members to be resolved with respect to an orthogonal stationary coordinate system.

Although the Swift® transducer is well suited for measuring loads reacted through the vehicle spindle on a vehicle such as passenger cars, the load cell cannot generally be used on a large vehicle such as an over-the-road truck due to a large spindle diameter on the truck leaving little clearance between the spindle and the tire rim.

There is thus an on-going need to provide an improved compact load cell, which can be used on large vehicles and is yet easy to manufacture.

SUMMARY OF THE INVENTION

One embodiment of the present invention is a load cell body for transmitting forces and moments in a plurality of directions. The load cell body is an integral assembly having a first ring member and a second ring member. Each ring member has a central aperture centered on a reference axis. Three or more tubes extend from the first ring member to the second ring member parallel to the reference axis.

Another embodiment includes a wheel force load cell body for transmitting forces in a plurality of directions. The wheel force load cell body has an integral assembly with first and second ring members. Each ring member has a central aperture centered on a reference axis. In addition, at least three tubes extend from the first ring member to the second ring member parallel to the reference axis. The wheel force load cell body also includes a mounting hub with first and second annular rims. The mounting hub also has a cylindrical support extending between the first and second rims.

Yet another aspect of the present invention includes a method of making a load cell body. The method includes fabricating from a single block of material an integral assembly having a first annular ring, a second annular ring and a plurality of members spanning therebetween. Each includes a central aperture centered on a reference axis. The method further includes forming a bore within each member, wherein each bore is aligned with an aperture in at least one of the annular rings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1**A is a side elevational view of a load cell in accordance with the present invention.

FIG. **1**B is a rear elevational view of the load cell illustrated in FIG. **1**A.

FIGS. **2**A and **2**B are sectional views taken along line **2**—**2** of FIG. **1**A and include schematic diagrams illustrating placement of sensors on the load cell.

FIGS. **3**A and **3**B are schematic drawings of electrical circuits used to measure forces and moments about an orthogonal coordinate system.

FIG. **4**A is a sectional view of the load cell mounted to a tire rim.

FIG. **4**B is a front elevational view of the transducer.

FIG. **5** is a sectional view of the load cell mounted to the tire rim and including a slip ring assembly.

FIG. **6** is a general block diagram of a controller.

FIG. **7** is a block diagram of a scaling and geometric transformation circuit.

FIG. **8** is a circuit diagram of a portion of a cross coupling matrix circuit.

FIG. **9** is a block diagram of a coordinate transformation circuit.

FIG. **10**A is a sectional view of a second embodiment of a load cell mounted to a tire rim.

FIG. **10**B is a front elevational view of a second embodiment of a load cell.

FIG. **11** is a cross-sectional view illustrating two embodiments of overtravel stop assemblies.

DETAILED DESCRIPTION OF THE ILLUSTRATIVE EMBODIMENTS

FIGS. **1**A and **1**B illustrate a first embodiment of a load cell **10** of the present invention. The load cell **10** preferably includes an integral body **12** fabricated from a single block of material. The body **12** includes a first rigid annular ring **14** and a second annular ring **16** that is parallel and aligned with the first annular ring **14** so as to be centered about a common axis **15**. A plurality of tubes **20** join the first annular ring **14** to the second annular ring **16**. In the embodiment illustrated, the plurality of tubes **20** comprise eight tubes **21**, **22**, **23**, **24**, **25**, **26**, **27** and **28**. Each of the tubes **21**–**28** extend from the first annular ring **14** to the second annular ring **16** parallel to the axis **15**. Although illustrated wherein the plurality of tubes **20** equals eight, it should be understood that any number of tubes three or more can be used to join the first annular ring **14** to the second annular ring **16**. In the embodiment illustrated, the plurality of tubes **20** are spaced at substantially equal angular intervals about the axis **15**.

A plurality of sensors **30** are mounted on the plurality of tubes **20** to sense strain therein. In the embodiment illustrated, sixty-four strain gauges are incorporated in sixteen Wheatstone bridges, wherein two Wheatstone bridges are provided for each tube **21**–**28**. The sixteen Wheatstone bridges are combined into eight strain gauge signals that are provided as an output from the load cell **10**. For purposes of explanation, an orthogonal coordinate system **31** can be defined wherein an X-axis is indicated at **33**, a Z-axis is indicated at **35**, and a Y-axis corresponds to the central axis **15**. The eight strain gauge signals from the load cell **10**, as explained below, are used to calculate forces along and about the X-axis **33**, the Y-axis **15** and the Z-axis **35**.

Generally, measurement of the forces along the X-axis **33** and the Z-axis **35** are measured from sensors in shear; forces along the Y-axis **15** are measured from sensors in axial tension/compression (preferably both axial and Poisson gauges are provided in the bridge); moments about the central axis **15** are measured from sensors in shear; and moments about the X-axis **33** and the Z-axis **35** are measured from sensors in differential axial strain. Each tube **21**–**28** includes strain sensors, preferably, mounted approximately at the center of the longitudinal length of each tube. Although strain sensors are mounted conventionally to provide an output signal indicative of shear stresses (e.g. sensors **29**A and/or sensors **29**B indicated in FIG. **1**A) in the walls of the plurality of tubes **20**, other forms of sensors such as those that provide an indication of bending stresses can also be used as appreciated by those skilled in the art such sensors being mounted at the transitions from the tubes **20** to the rings **14** and **16**. In addition, the plurality of sensors **30** comprise resistive strain gauges in the embodiment illustrated; however, other forms of sensing devices such as optically based sensors or capacitively based sensors can also be used.

In a preferred embodiment, each of the tubes **21**–**28** includes a plurality of spaced-apart wall portions of reduced thickness to concentrate stress therein. Referring to FIGS. **2**A and **2**B and tube **21** (FIG. **2**A) by way of example, the tube **21** has a non-rectangular outer surface **31** wherein the wall portions of reduced thickness are indicated at **33**A, **33**B, **33**C and **33**D. The wall portions of reduced thickness **33**A–**33**D are formed by a cylindrical bore **75** in the tube **21** and a first pair of parallel planar surfaces **37**A and **37**B facing in opposite directions and a second set of planar surfaces **39**A and **39**B also facing in opposite directions. The second set of planar surfaces **39**A and **39**B are substantially orthogonal to the first set of planar surfaces **37**A and **37**B such that the planar surfaces of the first set and the second set are alternately disposed about the corresponding longitudinal axis of tube **21**. Although illustrated wherein the thickness of the portions **33**A–**33**D are approximately equal, if desired, the thickness can be made different to provide desired sensitivity in selected directions. Preferably, the thickness of portion **33**A should be approximately equal to portion **33**C, and the thickness of portion **33**B should be approximately equal to portion **33**D.

The strain sensors are mounted on the first pair of parallel planar surfaces **37**A and **37**B and the second set of planar surfaces **39**A and **39**B. Planar mounting surfaces can be advantageous because measured output signals have lower hysteresis and lower creep gauge bonding due to uniform gauge clamp pressure on flat surfaces versus curved mounting surfaces, which locks residue stress in gauge. Also, alignment scribing and affixing of the gauges to the scribed lines is more difficult on a curved surface. The non-rectangular outer surface **31** is also beneficial because this form concentrates stress in portions of the tube **21**, which are proximate the strain sensors. Although a tube having a rectangular cross-section (four flat surfaces that intersect at the corners) can be used, significant stress concentration occurs at the intersection of the flat surfaces where strain sensors cannot be easily mounted. Thus, performance is substantially reduced. In contrast, the non-rectangular tube **21** illustrated in FIG. **2**A includes planar surfaces **41**A, **41**B, **41**C and **41**D that extend between each planar surface of the first set and the successive planar surface of the second set. In a preferred embodiment, the planar surfaces **37**A, **37**B, **39**A, **39**B and **41**A–**41**D preferably form an octagon in cross-section. Forming each of the tubes **21**–**24** with an octagonal outer surface **31** simplifies construction and reduces manufacturing costs since the planar surfaces can be easily machined. Although illustrated wherein one planar surface extends between each planar surface of the first set and successive surface of the second set, for example, planar surface **41**A, it should be understood that a plurality of intervening planar surfaces can be used. Similarly, the flat planar surfaces **41**A–**41**D can be replaced with curved wall portions to form a non-rectangular tube. Such a tubular structure does not have an annular wall of uniform thickness, but rather the spaced-apart portions of reduced wall thickness **33**A–**33**D again created by the flat surfaces **37**A, **37**B, **39**A and **39**B concentrate stress therein similar to the octagonal cross-section.

It should also be understood that different structures for the plurality of tubes **20** may be used in the load cell body. For example, outer surfaces of the plurality of tubes **20** may be constructed with concave outer surfaces similar to those described in U.S. patent application Ser. No. 09/518,290, filed on Mar. 3, 2000, entitled "Multi-Axis Load Cell", which is hereby incorporated by reference. In particular, the wall portions of reduced thickness **33**A, **33**B, **33**C and **33**D would each include an outer concave surface. As used herein, "concave" is not limited to a portion of an inner surface of a hollow sphere, but includes all outwardly opening curved surfaces, for example, cylindrical, parabolic, elliptical, etc. The wall portions of reduced thickness **33**A–**33**D are formed by a cylindrical bore in the radial tube and a first pair of concave outer surfaces (similarly disposed as surfaces **37**A and **37**B) facing in opposite directions and a second set of concave outer surfaces (similarly disposed as surfaces **39**A and **39**B) also facing in opposite directions. Use of the concave outer surfaces and the straight bores can have the advantage of providing gradual stress concentration to the wall portions of reduced thickness. In addition, since the thickness of the walls from the wall portions of reduced thickness increases greatly over a small distance from the portions of reduced thickness, the structure is stiffer for overturning moments.

The load cell body **12** can be manufactured from aluminum, titanium, 4340 steel, 17-4 pH stainless steel or other high-strength materials.

FIGS. **2**A, **2**B, **3**A and **3**B illustrate location and connection of the strain gauges into the sixteen Wheatstone bridges mentioned above. Generally, each tube includes a first pair of strain sensors **50** provided on a first portion (surface **37**A) of each tube **21**–**28**. A second pair of strain sensors **52** is provided on a second portion (surface **37**B) approximately 180 degrees from the first pair of strain sensors **50**. The first and second pairs of strain sensors on each tube **21**–**28** are connected in a conventional Wheatstone bridge to form a first sensing circuit on each tube **21**–**28**. The first Wheatstone bridge senses forces along one of the axes **33** or **35**. Specifically, in the embodiment illustrated, forces along the X-axis **33** are calculated from output signals from the first Wheatstone bridge provided on each of the tubes **21**, **22**, **25** and **26**. Similarly, output signals from the first Wheatstone bridge on each of the tubes **23**, **24**, **27** and **28** are used to calculate forces along the Z-axis **35**. Each of the first Wheatstone bridge circuits are shear sensing circuits. A second sensing circuit on each of the tubes **21**–**28** sense axial tension/compression along the Y-axis **15**. Each of the second Wheatstone bridge circuit includes a third pair of sensors **54** mounted on a third portion (surface **39**B) approximately 90 degrees from the first pair of sensors **50**, while a fourth pair of sensors **56** is mounted on a fourth portion (surface **39**A) approximately 180 degrees from the third pair of sensors **54**. In the embodiment illustrated, two poisson gauges in each of the second Wheatstone bridges (axial bridges) are not fully active like all of the sensors in the first Wheatstone bridges (shear bridges).

FIGS. **3**A and **3**B are schematic diagrams illustrating connection of the Wheatstone bridges on tubes **21**–**28** in order to realize eight output signals from the load cell **10**. In essence, pairs of similar sensing Wheatstone bridge circuits are connected together to provide an output signal of a virtual tube disposed between each of the tubes. For instance, a first Wheatstone bridge circuit **218** of tube **21** is indicated at **401** in FIG. **2**A, while a first Wheatstone bridge circuit **220** of tube **22** is indicated at **403** in FIG. **2**B. The Wheatstone bridges **218** and **220** effectively form a single output signal for a virtual tube **402** located between tubes **21** and **22** in FIGS. **2**A and **2**B. Resistors **278** and **280** are provided and chosen to match sensitivity of each of the Wheatstone bridge circuits **218** and **220** in order to combine the outputs thereof and effectively form one output signal.

The remaining fourteen Wheatstone bridges are similarly combined in pairs as illustrated in FIGS. **3**A and **3**B. Specifically, first Wheatstone bridge circuits **226** and **228** of tubes **23** and **24**, respectively, are combined to effectively form an output indicated at **405**; first Wheatstone bridge circuits **234** and **236** of tubes **25** and **26**, respectively, are combined to effectively form an output signal for a tube indicated at **408**; first Wheatstone bridge circuits **210** and **212** of tubes **27** and **28**, respectively, are combined to effectively form an output signal of a tube indicated at **411**; second Wheatstone bridge circuits **222** and **224** of tubes **21** and **22**, respectively, are combined to effectively form a second output signal for a tube indicated at **402**; second Wheatstone bridge circuits **230** and **232** of tubes **23** and **24**, respectively, are combined to effectively form a second output signal for a tube indicated at **405**; second Wheatstone bridge circuits **238** and **240** of tubes **25** and **26**, respectively, are combined to effectively form a second output signal for a tube indicated at **408**; and second Wheatstone bridge circuits **214** and **216** of tubes **27** and **28**, respectively, are combined to effectively form a second output signal for a tube indicated at **411**. Resistors **270**, **272**, **274**, **276**, **282**, **284**, **286**, **288**, **290**, **292**, **294**, **296**, **298** and **300** are used in a manner similar to resistors **278** and **280** to match sensitivity.

As appreciated by those skilled in the art, it is not necessary that the Wheatstone bridge circuits be combined as illustrated in FIGS. **3**A and **3**B in order to practice the present invention. In other words, the output signal provided by each Wheatstone bridge can be obtained wherein suitable hardware or software is used to resolve each of the corresponding output signals with respect to the coordinate system of orthogonal axes **33**, **35** and **15**. However, connection of the Wheatstone bridges as described above and illustrated in FIGS. **2**A and **2**B can realize manufacturing cost savings by reducing the number of output signals provided from the load cell **10**.

In the embodiment illustrated, the load cell **10** provides eight signals as described above. The eight signals are then transformed to provide forces and moments about the axis of the coordinate system **31**. Specifically, force along the X-axis **33** is measured as principal strains due to shear stresses created in tubes **21**, **22**, **25** and **26**. This can represented as:

$$F_x = F_{x1} + F_{x2};$$

where the outputs F_{x1} and F_{x2} are obtained as indicated in FIG. **3**A.

Similarly, force along the Z-axis **35** is measured as principal strains due to shear stresses created in the tubes **23**, **24**, **27** and **28**. This can be represented as:

$$F_z = F_{z1} + F_{z2};$$

where the outputs F_{z1} and F_{z2} are obtained as indicated in FIG. **3**B.

Force along the Y-axis **15** is measured as axial tension/compression created in all of the tubes **21**–**28**. This can be represented as:

$$F_y = F_{y1} + F_{y2} + F_{y3} + F_{y4}$$

where the outputs F_{y1}, F_{y2}, F_{y3} and F_{y4} are obtained as indicated in FIGS. **3**A and **3**B.

An overturning moment about the X-axis is measured as axial tension/compression forces created in tubes **21**, **22**, **25** and **26** from the opposed forces applied thereto. This can be represented as:

$$M_x = F_{y1} - F_{y3}.$$

Note, that the outputs indicative of F_{y2} and F_{y4} are effectively zero since each of these outputs are formed from tubes on each side of the X-axis **33**.

Likewise, an overturning moment about the Z-axis **35** is measured as axial tension/compression created in tubes **23**, **24**, **27** and **28** from the opposed forces applied thereto. This can be represented by:

$$M_z = F_{y4} - F_{y2}.$$

Note that for a moment about the Z-axis **35**, the outputs F_{y1} and F_{y3} are zero.

An overturning moment about the Y-axis **15** is measured as principal strains due to shear stresses created in all of the tubes **21**–**28**. This can be represented as:

$$M_y = (F_{x1} - F_{x2}) + (F_{z1} - F_{z2}).$$

It should be understood that the number of sensors **30** and the number of sensing circuits can be reduced if measured forces and moments of less than six degrees of freedom is desired.

The load cell **10** is particularly well-suited for measuring the force and moment components of a rolling wheel. Referring to FIGS. **4**A and **4**B, the load cell **10** is illustrated as being connected in the load path from a vehicle spindle **80** to a wheel rim **70**. In effect, the load cell **10** replaces a center portion of the rim **70**.

As illustrated, the tubes **20** are each oriented substantially parallel to a spindle axis corresponding substantially to the Y-axis **15**. Having the tubes **20** oriented as such allows the load cell **10** to carry larger moments as the tubes **20** are in tension/compression loading versus the bending/shear loading of a regularly oriented sensing element such as disclosed in U.S. Pat. No. 5,969,268. In addition, many vehicles such as medium and heavy-duty trucks have rims with large lug nut bolt circles (fasteners used to mount the truck rim to the spindle) and relatively small rim diameters, which do not allow use of radially oriented sensing members such as disclosed in U.S. Pat. No. 5,969,268. In contrast, the load cell **10** as illustrated has a relatively large inside diameter to accommodate the large lug nut bolt circles, and a relatively small outside diameter to allow fastening to the vehicle rim.

As illustrated in FIGS. **4**A and **4**B, the first annular ring **14** is secured to the rim **70**, while a hub adapter **74** joins the second annular ring **16** to a vehicle spindle **80**. Fasteners **72** joining the rim **70** to the first annular ring **14** can be secured at any desired location in the first annular ring **14**; however, in order to concentrate loading directly into each of the tubes **20**, it may be preferable to secure the fasteners **72** to the first annular ring **14** so as to be oriented in line with a bore **75** of each of the tubes **20**. In the embodiment illustrated, each aperture of the first annular ring **14** is aligned with an opening to a bore **75** of each tube **21**–**28** and includes a mounting element **76** that is secured in the corresponding aperture. For instance, as illustrated, the mounting element **76** can comprise a threaded plug that engages threads provided in the corresponding aperture in the first annular ring **14**. The fastener **72** can then threadably mate with threads provide in the mounting element **76**. If desired, the mounting element **76** can be secured in the aperture by other means such as welding, braising, gluing, bonding or the like. Raised portions **39** extending slightly above surface **36** of annular ring **14** can be provided to concentrate stresses thereon proximate each tube **21**–**28** (FIG. **1**B). Similar raised portions can be provided for mounting the load cell body **10** to rim **70**. Extending flanges **41** can be provided to center the load cell body **10** on the rim **70** (FIG. **1**A).

The second annular ring **16** can be secured to the hub adapter **74** in a manner similar to connection of the first annular ring **14** to the rim **70**. In the embodiment illustrated, fasteners **78** secure the hub adapter **74** to the second annular ring **16** using a mounting element **75** similar to mounting element **76**. The hub adapter **74** transmits loads between the load cell **10** and the vehicle spindle **80**. The hub adapter **74** includes an inner annular ring **282** having apertures that can receive studs **284** present on the vehicle spindle **80** wherein lug nuts **285** secure the hub adapter **74** to the vehicle spindle **80**. A cylindrical portion **286** with reinforcing ribs **287** joins the inner ring **282** to an outwardly radially extending flange **288** or ring portion, which is secured to the load cell **10** as described above.

Outer cylindrical cover **40** and inner cylindrical cover **42** can also be provided on load cell **10** in order to protect the plurality of tubes **20**. Outer cover **40** and inner cover **42** can be secured and bridged between first annular ring **14** and second annular ring **16**. Covers **40** and **42** can be secured on the load cell body using adhesive such as silicone or other suitable fasteners that allow flexibility, yet prevent unwanted entry of dirt or other objects from coming into contact with the plurality of tubes **20** and, in particular, the plurality of sensors **30**. The covers **40** and **42** used in this manner form a sealed chamber for the tubes **21**–**28**.

Referring to FIG. **5**, power is supplied to and output signals are obtained from the plurality of sensors **30** by a controller **82** through a slip ring assembly **84**, if the tire rim **70** rotates or partially rotates. The controller **82** calculates, records and/or displays the force and moment components measured by the load cell **10**.

Load cell **10** includes amplifying circuits **71** and **73**. The amplifying circuits **71** and **73** are connected to the plurality of sensors **30** on the tubes **21**–**28** and amplify the output signals prior to transmission through the slip ring assembly **84**. By amplifying the output signals, problems associated with noise introduced by the slip ring assembly **84** are reduced. Referring to FIGS. **4**B and **5**, connectors **79**, **80**, **81** and **82** mounted in apertures **83**, **84**, **85** and **86**, respectively, connect the amplifying circuits **71** and **73** to the slip ring assembly **84**. A mounting plate **87** mounts the slip ring assembly **84** to the second annular ring **16**. Passageways such as **87**A and **87**B are provided in the mounting plate **87** to carry conductors from the slip ring assembly **84** to the connectors **79** and **81**. An encoder **89** provides an angular input signal to the controller **82** indicative of the angular position of the load cell **10**.

FIG. **6** illustrates generally operation performed by the controller **82** to transform the output signals **88** received from the individual sensing circuits on the tubes **21**–**28** to obtain output signals **108** indicative of force and moment components with respect to six degrees of freedom in a static orthogonal coordinate system. As illustrated, output signals **88** from the sensing circuits are received by a scaling and geometric transformation circuit **90**. The scaling and geometric transformation circuit **90** adjusts the output signals **88** to compensate for any imbalance between the sensing circuits. Circuit **90** also combines the output signals **88** according to the equations given above to provide output signals **94** indicative of force and moment components for the orthogonal coordinate system.

Referring back to FIG. **6**, a cross-coupling matrix circuit **96** receives the output signals **94** and adjusts the output signals so as to compensate for any cross-coupling effects. A coordinate transformation circuit **102** receives output signals **100** from the cross-coupling matrix circuit **96** and an angular input **104** from an encoder or the like. The coordinate transformation circuit **102** adjusts the output signals **100** and provides output signals **108** that are a function of a position of the load cell **10** so as to provide force and moment components with respect to a static orthogonal coordinate system.

FIG. **7** illustrates the scaling and geometric transformation circuit **90** in detail. High impedance buffer amplifiers **110**A to **110**H receive the output signals **88** from the slip ring assembly **84**. In turn, adders **112**A to **112**H provide a zero adjustment while, preferably, adjustable amplifiers **114**A to **114**H individually adjust the output signals **88** so that any imbalance associated with physical differences such as variances in the wall thickness of the location of the strain sensors **30** on the tubes **21**–**28** or variances in the placement of the sensors **30** from tube to tube can be easily compensated. Adders **116**A to **116**H combine the output signals from the amplifiers **114**A to **114**H in accordance with the equations above. Adjustable amplifiers **118**A to **118**D are provided to ensure that output signals from adders **116**A to **116**D have the proper amplitude.

As stated above, cross-coupling compensation is provided by circuit **96**. By way of example, FIG. **8** illustrates cross-coupling compensation for signal F_x. Each of the other output signals F_y, F_z, M_x, M_y, and M_z are similarly compensated for cross-coupling effects.

FIG. **9** illustrates in detail the coordinate transformation circuit **102**. The encoder **89** provides an index for sine and cosine digital values stored in suitable memory **120** and **122** such as RAM (Random Access Memory). Digital to analog converters **124** and **126** received the appropriate digital values and generate corresponding analog signals indicative of the angular position of the load cell **10**. Multipliers **128**A to **128**H and adders **130**A to **130**D combine force and moment output signals along and about the X-axis and the Z-axis so as to provide force and moment output signals **108** with respect to a static orthogonal coordinate system.

At this point, it should be noted that the load cell **10** of the present invention is not limited to the embodiment illustrated in FIGS. **1**–**5**. FIGS. **10**A and **10**B illustrate another form of a load cell **300** that can also be used for measuring force and moment components of a rolling wheel. Like the load cell **10** described above, the load cell **300** also includes an integral body **302** formed of a first ring member **304**, a second ring member **306** and a plurality of sensing tubes **310** joining the first ring member **304** to the second ring member **306**. Tubes **310** are constructed in a manner similar to that described above and include sensing elements as described above. However, in this embodiment, the first annular ring **304** includes a mounting flange **308** extending radially inwardly that can be used to secure the load cell **300** directly to the vehicle spindle **80**. Specifically, the annular ring **304** includes apertures that receive the studs **284** of the vehicle spindle wherein lug nuts **285** secure the annular ring **304** to the vehicle spindle **80**. In this embodiment, a cylindrical rim extender **330** joins the second annular ring **306** to the vehicle rim **70** and can be mounted to the second annular ring **306** in a manner similar to that described above with fastener **318** wherein mounting elements **314** are provided in apertures opening to bores forming each of the plurality of tubes. Otherwise, other fastening techniques such as welding can be used although some form of removable fastener is generally preferred.

FIG. **11** illustrates two embodiments of overtravel stop assemblies **174** and **176** that can be incorporated into the loads cell **10** and **300**, if desired. Referring first to overtravel stop assembly **174**, the assembly includes extension elements **182** and **184** secured within the bore **75** extending from the first annular ring **14** to the second annular ring **16**. First ends **186** and **188** of each extension element **182** and **184**, respectively, are secured to the first annular ring **14** and the second annular ring **16**, respectively. The extension elements **182** and **184** extend toward each other within the bore **170** such that ends **190** and **192** are positioned proximate each other. In the embodiment illustrated, extension element **182** includes a recess having a shape and size suitable for receiving the end **192** with slight clearance. A fastener **194** such as a threaded bolt herein depicted, limits axial displacement of the extension elements **182** and **184** away from each other. The fastener extends through a bore **196** provided in the extension element **182** with slight clearance and is secured to the extension element **184** with a threaded aperture **198**.

Extension elements **182** and **184** can be secured within corresponding apertures of the first annular ring **14** and the second annular ring **16** using conventional techniques such as welding, braising, bonding or gluing. In the embodiment illustrated, mating threads formed on the extension elements **182** and **184** and on apertures formed in the first annular ring **14** and the second annular ring **16** are used to secure the elements. Fasteners **72** and **78** can threadably mate with threads **183** and **185** in manner discussed above with respect to mounting element **75** and **76**.

Extension elements **182** and **184** can also act as a thermal conductive shunt between the first annular ring **14** and the second annular ring **16** in addition to functioning as an overtravel stop. If desired, a thermally conductive grease can be provided between ends **190** and **192** in order to enhance thermal conductivity.

Assembly **176** is similar to assembly **174** and includes extension elements **200** and **202** having first ends **204** and **206** thereof secured to the first annular ring **14** and the second annular ring **16**, while second ends **208** and **210** thereof are positioned proximate each other. In this embodiment, a fastener **212** comprises a threaded bolt **214** and a threaded nut **216**. The fastener **212** extends through a bore **218** formed in the second end **208** of the extension element **200** with slight clearance. The nut **216** also extends through a bore **220** formed in the second end of the extension element **202** with slight clearance. The nut **216** is secured to the extension element **202** with the bolt **214**. The nut **216** includes a portion **222** comprising an extending flange of size greater than the bore **220** of extension element **202**. Contact of the extending flange of the nut **216** with an inner wall of the bore **220**, herein conically shaped, will limit axial displacement of the extension elements **200** and **220** away from each other.

It should be noted that whether functioning as an overtravel stop and/or a thermal conductive shunt, either of the assemblies **174** and **176** can be incorporated in tubular sensing structures such as a plurality of tubes **20** of the load cell **10** herein illustrated, or in other load cells having tubular sensing structures such as disclosed in U.S. Pat. No. 5,969,268 (the content of which is herein incorporated by reference in its entirety) wherein the load cell includes radially oriented tubes extending from a center hub to an annular ring.

Although illustrated wherein the second ends **190**, **192**, **209** and **210** are approximately disposed at the midpoint of each corresponding tube, those skilled in the art will appreciate that this is not necessary and that positioning of the ends of the elements can be disposed anywhere along the length of the bore formed in the tubes. The load cell **300** of FIGS. **10**A and **10**B could also include the assemblies **174** and **176**, if the bores forming the tubes **304** are extended through the first annular ring **304**.

Although the present invention has been described with reference to preferred embodiments, workers skilled in the art will recognize that changes may be made in form and detail without departing from the spirit and scope of the invention.

What is claimed is:

1. A load cell body for transmitting forces and moments in a plurality of directions, the load cell body comprising:

an integral assembly having:
  a first ring member and a second ring member, each ring member having a central aperture centered on a reference axis;
  at least three tubes extending from the first ring member to the second ring member parallel to the reference axis; and
  wherein the first ring member includes an aperture aligned with an opening to a bore in each of the tubes.

2. The load cell body of claim **1** and further comprising sensors mounted on selected tubes.

3. The load cell body of claim **2** wherein the sensors comprise shear sensors and axial tension/compression sensors mounted to each tube.

4. The load cell body of claim **2** wherein an outer surface of each tube includes a plurality of opposed surfaces and wherein the sensors are mounted to the opposed surfaces.

5. The load cell body of claim **4** wherein the outer surface comprises a first pair of surfaces facing in opposite directions and a second set of surfaces facing in opposite directions, the second set of surfaces being substantially orthogonal to the first set of surfaces such that the surfaces of the first set and the second set are alternately disposed about each corresponding longitudinal axis and wherein the sensors are mounted to the surfaces of the first and second sets of surfaces.

6. The load cell body of claim **5** wherein eight tubes join the first ring member to the second ring member, and wherein opposed surfaces of adjacent pairs of tubes are aligned such that the first pair of opposed surfaces face the same direction and the second pair of opposed surfaces face the same direction.

7. The load cell body of claim **6** wherein each of the opposed surfaces is planar.

8. The load cell body of claim **6** wherein the outer surfaces of each tube form an octagon.

9. The load cell body of claim **6** wherein the sensors comprise a set of shear sensors mounted on the first set of opposed surfaces comprising a shear sensing circuit for each tube, and a set of axial tension/compression sensors mounted on the second set of opposed surfaces comprising a axaial tension/compression sensing circuit for each tube.

10. The load cell body of claim **9** wherein the shear sensing circuits of each of said adjacent pairs of tubes are electrically coupled to provide an output signal, and wherein the axial tension/compression sensing circuits of each of said adjacent pairs of tubes are electrically coupled to provide an output signal.

11. The load cell body of claim **2** wherein the sensors comprise bending sensors.

12. The load cell body of claim **1** wherein the second ring member includes an aperture aligned with an opening to each bore of the tubes.

13. The load cell body of claim **12** wherein at least some of the apertures in the first and second ring members aligned with the bores include mounting threads.

14. The load cell body of claim **1** and further comprising:

a mounting hub including a first annular rim joined to the first ring member, a second annular rim including a plurality of bores extending there through and a cylindrical support extending between the first annular rim and the second annular rim.

15. The load cell body of claim **1** wherein an outer surface of each tube is non-rectangular.

16. The load cell body of claim **1** wherein at least some of the apertures in the first ring member aligned with the bores include mounting threads.

17. A load cell body for transmitting forces and moments in a plurality of directions, the load cell body comprising:

an integral assembly having:

a first ring member and a second ring member, each ring member having a central aperture centered on a reference axis; and

at least three tubes extending from the first ring member to the second ring member parallel to the reference axis;

an inner cylindrical wall plate joined to at least one of the first and second ring members; and

an outer cylindrical wall plate joined to at least one of the first and second ring members, wherein the plurality of tubes are disposed between the inner and outer cylindrical wall plates.

18. The load cell body of claim **17** wherein inner and outer cylindrical wall plates are joined to the first and second ring members to form a sealed chamber.

19. The load cell body of claim **17** and further comprising sensors mounted on selected tubes.

20. The load cell body of claim **19** wherein the sensors comprise shear sensors and axial tension/compression sensors mounted to each tube.

21. The load cell body of claim **19** wherein an outer surface of each tube includes a plurality of opposed surfaces and wherein the sensors are mounted to the opposed surfaces.

22. The load cell body of claim **21** wherein the outer surface comprises a first pair of surfaces facing in opposite directions and a second set of surfaces facing in opposite directions, the second set of surfaces being substantially orthogonal to the first set of surfaces such that the surfaces of the first set and the second set are alternately disposed about each corresponding longitudinal axis and wherein the sensors are mounted to the surfaces of the first and second sets of surfaces.

23. The load cell body of claim **22** wherein eight tubes join the first ring member to the second ring member, and wherein opposed surfaces of adjacent pairs of tubes are aligned such that the first pair of opposed surfaces face the same direction and the second pair of opposed surfaces face the same direction.

24. A load cell body for transmitting forces and moments in a plurality of directions, the load cell body comprising:

an integral assembly having:

a first ring member and a second ring member, each ring member having a central aperture centered on a reference axis; and

at least three tubes extending from the first ring member to the second ring member parallel to the reference axis; and

an overtravel limit assembly extending within a bore of a tube.

25. The load cell body of claim **24** wherein the overtravel limit assembly comprises a first extension joined to the first ring member and a second extension joined to the second ring member, a coupling device selectively coupling the first and second extension members to limit displacement of the first extension from the second extension.

26. The load cell body of claim **25** wherein the first extension member and the first ring member include mating threads and the second extension member and the second ring member include mating threads.

27. The load cell body of claim **26** wherein the first and second extension members each include central recesses with inner threads.

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